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The Accuracy of Orthophotos and Simultaneously Collected Terrain Height Data

The effect of height errors, and filtering techniques for correcting those errors, are described.

Abstract: *The results of the International Orthophoto Experiment of the ISP Working Group II/4 differ widely in the accuracy of height data obtained during differential rectification. The times indicated for profiling also vary. Both height accuracy and scanning speed can be increased significantly if dynamic errors are corrected by digital filters. The dynamic error to be expected from electronic image correlators is smaller, too, because the machine responds faster than human operators.*

Introduction

Differential rectification using a constantly moving scanning slit that traverses the model in a meander pattern has proved to be the most economic technique for deriving true-to-scale photomaps from aerial photographs. Most map users, however, need maps containing height information. Orthophotography is based on height information in the form of profiles. Therefore, all instrument manufacturers provide for facilities to store profile data during profiling and to derive contour maps from the data thus stored. Storing may be effected digitally (punched tape, magnetic tape) or graphically (droplines, profile storage plates), either directly during profiling or through peripheral equipment.

In profiling, the model is scanned in x and y by motor systems, while vertical follow-up (z) is controlled either by the operator or by an electronic image correlator. One of the coordinates (y, as a rule) is varied continuously, so that the differential rectification system is actually a closed-loop control system involving a dynamic measuring process, which influences the accuracy of the height data.

Influence of Sampling Error on the Orthophoto Accuracy

In orthophotography, a height error causes a radial displacement Δr of image details. Δr varies with the inclination angle of the projection ray and with radial terrain slope α_r according to the equation

$$\Delta r = \frac{\Delta z \cdot r}{z - r \tan \alpha_r} \qquad (1)$$

where z and r are the coordinates at the orthophoto scale (Figure 1). Because of Δr, point (P) is imaged instead of P. Radial detail displacements in adjacent strips do not correlate so that visible discontinuities may occur at strip borders if the accuracy of vertical follow-up is insufficient. Equation 1 shows that higher sampling accuracy is required especially for terrain sloping down towards the margin, whereas a greater height error is tolerable near the center of the photograph. Therefore, the operator should have a facility for speed control within a profile. As a rule, however, he will use this facility as terrain configurations vary, irrespective of their positions in the photo. This is necessary also if height models of homogeneous accuracy are to be derived.

ACCURACY REQUIREMENTS OF A HEIGHT MODEL

To make first-quality orthophotos, the mean sampling error should not exceed 0.3 per thousand of the projection distance. That way, height models can be stored that meet national map accuracy standards. Studies (Macarovič, 1972; Marckwardt, 1976) have shown, that the height accuracy attainable depends on

- operator experience,
- instrument accuracy in dynamic mode of operation,
- mean rate of floating mark travel, and
- mean model slope.

The ISP Working Group II/4 (Blachut and van Wijk, 1976) published comparable values for various orthophoto printers, obtained in a joint experiment with instrument manufacturers, who compiled orthophotos and height information from photographs of a common test area. The profiling times stated by the manufacturers differ greatly. Although no information about the experience of the operators has been given, conclusions can be drawn for the optimum profiling speed referred to the photograph. The average speed for profiling the test area (terrain of average difficulty) is 1 mm/s, with variations between 0.6 and 1.5 mm/s. The evaluation of the height models supplied by the various manufacturers showed that most of them failed to attain the accuracy required for the German Base Map, which was used as a reference. The reason must be either too fast a scanning speed or insufficient instrument accuracy in the dynamic mode of operation.

PROCEDURES TO IMPROVE THE ACCURACY OF HEIGHT DATA

DYNAMIC ERRORS

The scanning speed will influence the accuracy of profile data and the productivity of the process. Remedies must be sought to decrease height errors in profiling and to improve scanning speed. A simple experiment will prove that profile scanning involves systematic dynamic errors: Have one operator scan the same terrain profile several times, and find the mean square error from the differences, d, between each two of the records by using the equation

$$m = \pm\sqrt{\frac{[d\,d]}{2\,n}}\,. \tag{2}$$

Let m_1 be the mean square error found for profiling runs of identical direction, and m_2 the mean square error found for runs of opposite direction. The significant difference between m_1 and m_2 suggests systematic errors caused by the dynamic measuring process (Figure 2). On contour maps, such errors effect oscillations of the contours across the scanning direction.

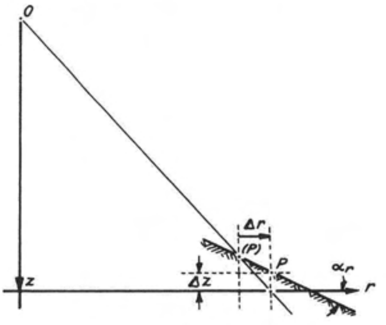

FIG. 1. Relationship between planimetric and height errors in the orthophoto.
Δz—height error at point P
Δr—radial planimetric shift of point (P)
α_r—radial slope angle between (P) and P
z—projection distance

FILTERING OF DIGITAL DATA

Height information digitally stored on machine-readable data carriers (punched tape, magnetic tape) can be corrected for systematic errors by digital filters, in order to improve height accuracy or to increase scanning speed.

Across-the-profile smoothing filters. In the simplest case, with the floating mark travelling in a meander pattern and data recording in an x,y-raster, linear filters according to Equations 3 or 4 can be employed for across-the-profile smoothing:

$$\overset{*}{z}_{j+1/2,i} = \frac{z_{j,i} + z_{j+1,i}}{2} \tag{3}$$

$$\overset{*}{z}_{j,i} = \frac{z_{j-1,i} + 2\,z_{j,i} + z_{j+1,i}}{4} \tag{4}$$

where j = number of profile ($j = 1 \cdots m$), and i = number of a point in the profile ($i = 1 \cdots n$).

Height models processed with these filters yield an improved contour pattern with smooth contours. In case of widely spaced profiles, however, terrain configurations will be smoothed, too, so that there is no resulting increase in accuracy even though dynamic errors are corrected.

To study the effect of Equation 4, static profile measurements were carried out in five models and the profiles were scanned dynamically together with two neighbouring profiles at intervals of 0, 1, 2, and 4 mm in the model. The comparison of the statical-

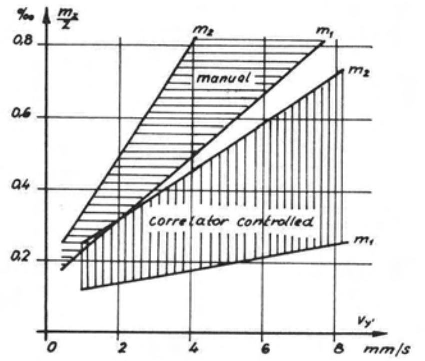

FIG. 2. Differences of mean square height errors m_1^* and m_2 (referenced to projection distance z) as a function of mean scanning speed v_y, in the photograph (average terrain elevation differences, average experience of the operator). Compilation with Jena Topocart-Orthophot.

ly measured heights (assumed to be true heights) with the dynamically measured (m_z) and the filtered ones (m_z^*) indicated that such filters will increase accuracy only if profile intervals, $\Delta x'$, do not exceed 2 mm (terrain of medium elevation differences). See Figure 3.

Recursion filters. It is more favorable to combine the digital filter with a dynamic model of the sampling process (Marckwardt, 1976):

$$\overset{*}{z} = z + \gamma_1\dot{z} + \gamma_2\ddot{z} \tag{5}$$

where z is the measured height; $\dot{z}$ and $\ddot{z}$ are the derivatives of the profile with respect to time; and γ_1, γ_2 is a parametric vector. Profile derivatives are found by parabolic interpolation between three consecutive points:

$$\frac{dz}{dt} = \dot{z} = \frac{z_{i+1} - z_{i-1}}{2\ \Delta t} \tag{6}$$

$$\frac{d^2z}{dt^2} = \ddot{z} = \frac{z_{i+1} - 2\,z_i + z_{i-1}}{\Delta t^2} \tag{7}$$

In meander scanning, with a rigorous x,y-raster and constant speed, Δt must be normalized ($\Delta t = 1$). A value z filtered according to Equation 4 will result for each recorded point $P_{j,i}$ ($j = 2 \cdots m-1, i = 1 \cdots n$), so that a number of $(m-2)n$ condition equations like Equation 5 can be established. The unknown parametric vector (γ_1, γ_2) and the corrections for each profile point are found by least-squares adjustment.

Alternatively, the self-calibrating filter described can be used in such a way that the entire data set is divided into sub-sets of 4 to 10 profiles each and (γ_1, γ_2) is calculated separately for each sub-set. This allows for changes of the parametric vector, caused, e.g., by operator fatigue, and permits the use of a computer of low storage capacity.

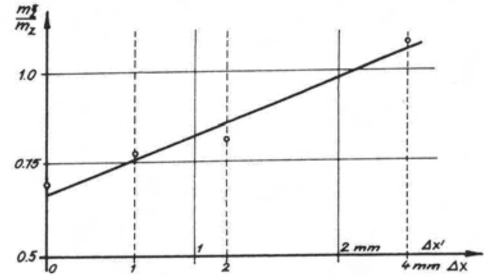

FIG. 3. Relative improvement of height accuracy by smoothing across the profile according to Equation 4.

m_z^*—mean square error of smoothed z-values
m_z—mean square error of dynamically measured z-values
$\Delta x'$—profile interval in the photograph
Δx—profile interval in the model

The parametric vector is different for each operator, depending on his experience and momentary constitution. In correlator-controlled scanning, the parametric vector remains constant over a longer period, so that filtering according to Equation 5 is possible in a real-time mode, the rigorous x,y-raster being replaceable by an x,t-raster. It should be noted, however, that γ_2 varies with Δt.

Experiments made with such filtering on a moderately complicated model allowed scanning speed to be increased by a factor of 1.6 (Marckwardt, 1976).

Filtering with two classes of reference points. In photogrammetry, the least-squares method is the most advanced and most expensive filtering technique in present use. It proceeds from an estimated or empirically established covariance function. If profiling follows a meander pattern, covariances vary not only with distance but also with the direction of floating mark travel. Kraus (1973) suggested, therefore, that the measured data be divided into two statistic sets, each characterized by a common scanning direction ($+y$, $-y$). The filter equations will then contain auto- and cross-covariances. The system of formulae is too complex to be given here.

Including the technique in the Stuttgart Contour Program has significantly improved the accuracy of height models derived by profiling. The contours of the above test area, established that way, are sufficiently accurate despite higher scanning speed (Blachut and van Wijk, 1976).

AUTOMATIC IMAGE CORRELATION

An electronic control-loop is much faster than a human operator in responding to

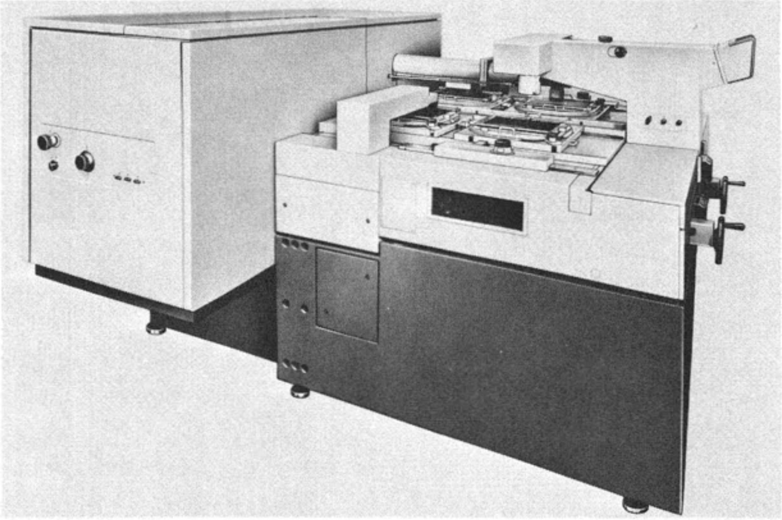

FIG. 4. Jena Topomat Automatic Stereorestitution System. The system comprises a modified Topocart plotter with Orthophot C orthoprinter, and the Oromat, an automatic image correlator.

variations of the input variables. If the operator of a sampling system is replaced by an electronic image correlator, a considerable reduction of dynamic errors can be expected. Figure 2 shows the differences between m_1 and m_2 obtained for the Jena Topocart/Orthophot system. It is evident from the graph that the electronic Oromat image correlator (Figure 4) allows scanning at a rate three times faster without any loss of internal accuracy (Szangolies and Kunze, 1977). Regrettably, none of the instruments included in the International Orthophoto Experiment had an image correlator operating by the dynamic principle of a moving slit. The scanning time for image correlators is not influenced by human operators and it would be possible to compare the instruments.

As a drawback of image correlators in case of large-scale photography, automatic height measurement is more than tolerably affected by vegetation, as the floating mark is always guided along the visible terrain surface. For the orthophoto this is of no consequence. It is much more important to have accurate continuity between adjacent profile strips, which in case of a meander profiling is described by m_2.

SUMMARY

Terrain height data obtained photogrammetrically together with differential rectification are affected by dynamic errors that limit scanning speed and coact with slit width in determining the time for profiling the model. The dynamic errors depend on several factors, the most important of which is the skill and experience of the operator. To reduce dynamic errors, digital filters can be employed. They allow scanning speed to be increased by a factor of 1.5···2. In addition, where electronic image correlators are used, dynamic influences are small, so that scanning speed may be increased by three times. A combination of image correlators and digital filters would be the optimum solution, provided that vegetation constitutes no disturbing factor in large-scale mapping.

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